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How to take time into account in the inventory step: a selective introduction based on sensitivity analysis

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Abstract
Purpose Life cycle assessment is usually an assessment tool, which only considers steady-state processes, as the temporal and spatial dimensions are lost during the life cycle inventory (LCI). This approach therefore reduces the environmental relevance of certain results, as it has been underlined in the case of climate change studies. Given that the development of dynamic impact methods is based on dynamic inventory data, it seems essential to develop a general methodology to achieve a temporal LCI.
Methods This study presents a method for selecting the steps, within the whole process network, for which dynamics need to be considered while others can be approximated by steady-state representation. The selection procedure is based on the sensitivity of the impacts on the variation of environmental and economic flows. Once these flows have been identified, their respective timescales are compared to the inherent timescales of the impact categories affected by the flows. The timescales of the impacts are divided into three categories (days, months, years) based on a literature review of the ReCiPe method. The introduction of a temporal dynamic depends on the relationship between the timescale of the environmental and economic flows on the one hand and that of the concerned impact on the other hand.
Results and discussion This approach is illustrated by the life cycle assessment of palm methyl ester and ethanol from sugarcane. In both cases, the introduction of a temporal dynamic is limited to a small proportion of the total number of flows: 0.1 % in the sugarcane ethanol production and 0.01 % in the palm methyl ester production. Future developments of time integration in the LCI and in the life cycle impact assessment (LCIA) are also discussed in order to deal with the need of characterization functions and the recurrent problem of waiting times.
Conclusions This work provides a method to select specific flows where the introduction of temporal dynamics is most relevant. It is based on sensitivity analyses and on the relationship between the timescales of the flows and the timescale of the involved impact. The time-distributed LCI generated by using this approach could then be coupled with a dynamic LCIA proposed in the literature.

Keywords Dynamic LCA · Life cycle impact assessment · Life cycle inventory · Perturbation analysis · Sensitivity analysis · Timescale

1 Introduction

Life cycle assessment (LCA) offers a clear and structured framework for the computation of impacts on the environment. Environmental damage can be assessed from a technical system description—life cycle inventory (LCI)—to the use of environmental cause–effect models—life cycle impact assessment (LCIA). The studied systems are entire life cycles, with many steps, and consequently, LCI is applied to steady-state and linear models of elementary processes (Udo de Haes 2006). Temporal and/or spatial variations of commodity flows and emissions are in most cases ignored in current LCA and are sometimes regarded as an important source of uncertainty (Huijbregts 1998).

Although the spatial dimension is becoming a key issue in LCA methodological developments, little attention has been given to temporal aspects of LCA, either in LCI or in LCIA. Nevertheless, dynamics have been identified as one of the main

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unresolved problems in LCA (Reap et al. 2008). During the LCI, the dynamics of the emissions are not modelled; consequently, the ensuing concentrations in the environment cannot be known. Although several methodological developments have been dedicated to spatial characteristics of the impacts (Hauschild and Potting 2005; Pfister et al. 2009) and their relative scales (Hauschild 2006), only a few studies concern the temporal inherent characteristics of the impacts. As underlined by McKone et al. (2011), each impact is associated with a natural timescale. At the LCIA step, time is in most cases present through time frames of integration (e.g. global warming potentials over 20, 100 or 500 years). In the current LCA framework, the biological processes are assumed to respond linearly to environmental disturbances, and therefore, threshold effects are neglected (Owens 1997). However, temporal factors (time of emissions and rate of release) have an effect on the impacts of pollution (Field et al. 2000; Owens 1997; Stasinopoulos et al. 2011). For instance, some impacts are subject to seasonal variations, such as aquatic eutrophication, which is higher in summer than in winter (Udo deHaes et al. 2002).

Time can be taken into account at different levels in LCA:

– At the functional unit level, by giving a time dimension to the functional unit (e.g. 1 h of light).
– At the LCI level, by using scenarios to model the inventory on a short-term or long-term period (Pesonen et al. 2000) and the evolution of technologies assessed during this period. It can also be done by assessing all the products in use rather than one single product to eliminate simplifying assumptions imposed upon the analysis by a product-centred approach (Field et al. 2000; Stasinopoulos et al. 2011).
– At the LCIA level, by choosing characterization functions instead of characterization factors. This approach is based on the development of time-dependent factors. According to the time when the emissions have been released (or the resources consumed), the magnitude of the generated impact is different. This has been done by Manneh et al. (2012) for the human toxicity impact and Shah and Ries (2009) for the photochemical oxidation impact. Special attention has been recently given to the climate change impact (Levasseur et al. 2011), with the developments of characterization functions by Levasseur et al. (2010) and Cherubini et al. (2011). The distinction between short-term emissions (less than 100 years) and long-term emissions (more than 100 years) also leads to different characterization factors according to the time horizon on which the impacts are assessed. The time integration can also be done by considering the modification of the background environment (and thus, the impact generated by the functional unit may change as a function of time). This approach has been developed for pollution induced by heavy metals by Hellweg et al. (2005) and for the acidification impact by van Zelm et al. (2007). Finally, time can be introduced at the level of optional elements of the LCIA as weighting the impacts (Hellweg et al. 2003), which can induce ethical problems such as intergenerational preferences, and at the normalization step, by choosing a perspective (individual, hierarchical or egalitarian) which defines the time horizon over which some impacts are assessed.

Dynamic LCIA requires dynamic LCI: temporally distributed emissions and resource consumptions are mandatory for the use of characterization functions at the LCIA step. In the present work, dynamic aspects have been only studied at the flow level of the inventory. The systematic introduction of dynamics at this level faces two limits:

– It implies the definition and validation of at least one dynamic model for each process whereas a LCA can involve hundreds of processes (and thousands of flows), which is time consuming. The data requirement and the complexity of the modelling of all the processes would also probably make this work very difficult (Udo de Haes et al. 2004).
– It requires the capacity to manipulate an important set of dynamic systems with a large number of interconnected variables and different time constants. Hence, computational aspects could be a tough issue.

To deal with these limits, the aim of this study is to set up a procedure to select the processes—within the whole LCI process network—for which taking into account the dynamics significantly affects the LCIA results. The approach confronts the most sensitive flows to the affected impact categories according to their inherent timescales.

The idea of the paper is not to deal with all the variability in the system, but it is focused on the main contributors affecting time. Flows (both environmental and economic) are key elements in LCA, and they are at the base of the whole computational approach of impact determination. Flows represent all the information described in the inventory and are a relevant means to take time into account in LCA. Variability may originate from many causes, but in the present approach, the idea is to select the sensitive flows according to the time aspect via two questions: Does this flow change over time? If the answer is positive, is this time variation relevant for the result (i.e. with a relevant effect at the LCIA level)?

After a brief recall of the mathematical structure of LCA, a selection of the most relevant flows is presented in the next section. Based on a literature review of the ReCiPe method, a classification of the timescales of the impacts can be proposed. The procedure is then applied to two large systems of bioenergy production from the Ecoinvent database.

2 Methods

2.1 Sensitivity analysis in LCA

2.1.1 Matrix formalism

The classical representation of the inventory analysis of a LCA is composed of (with p the number of processes, u the number of economic flows, e the number of emissions and m the number of impacts):

- A, a u-by-p matrix, named the technology matrix. As a multi-output process can be (1) split in accordance with a rule of attribution or (2) considered as a simple-output process by a substitutional approach with negative inputs, A is a square matrix of order u. Each line corresponds to an economic flow and each column to a process. We assume that the processes and the economic flow are ordered in the same way: elements of the diagonal of A are not null and correspond to the output of processes.
- B, an e-by-p matrix, named the intervention matrix. Each line corresponds to an environmental flow and each column to a process.
- f, a vector of dimension u, named the final demand vector. Each line corresponds to an economic flow. All lines are null except for that of the reference flow.
- s, a vector of dimension p, named the scaling vector. It is calculated with Eq. (1).

$$s = A^{-1} \times f \tag{1}$$

According to Heijungs and Suh (2002), the general calculation of an impact score is given by Eq. (2).

$$h = Q \times B \times A^{-1} \times f \tag{2}$$

where

- Q is an m-by-e matrix named the characterization factor matrix. Each line corresponds to an impact and each column to a characterization factor.
- h is a vector of dimension m, named the impacts vector. Each value corresponds to an impact score

The present approach proposes to consider the most sensitive couples {process | economic flow} and {process | environmental flow} with a perturbation factor analysis. This has to be done for all impacts, which implies a multi-criteria decision making (impact categories are in different units). Many approaches can be found in literature on this subject; in the present work, normalization in LCA has been chosen, as it allows dimensionless values for impact calculation (Goedkoop and Spriensma 2000).

2.1.2 Sensitivity analysis

For the impact l linked to a vector Q^l, the perturbation factor $\alpha_{i,j}{}^l$ in turn related to the economic flows $a_{i,j}$ is obtained with Eq. (3) (Heijungs 2010):

$$\forall (i,j,l) \in [1;p] \times [1;p] \times [1;m] \alpha_{i,j}^l = \frac{\partial h^l / h^l}{\partial a_{i,j} / a_{i,j}} \tag{3}$$

According to the differentiation rule for inverse matrices (e.g. Harville 1997 cited by Heijungs and Suh 2002), the following relationship can be obtained:

$$\frac{\partial (A^{-1})}{a_{i,j}} = -A^{-1} \times \frac{\partial A}{a_{i,j}} \times A^{-1} \tag{4}$$

This leads to:

$$a_{i,j}^l = -Q^l \times B \times A^{-1} \times \frac{\partial A}{a_{i,j}} \times s \times \frac{a_{i,j}}{h^l} \tag{5}$$

Substances can be emitted into the environment via several processes, and a process can generate several emissions; therefore, sensitivity analysis is done for a given environmental flow for a given unit process. If we consider a specific impact l linked to a vector Q^l, the perturbation factor $\beta_{k,j}^l$ related to the environmental flow $b_{k,j}$ is defined as follows (Heijungs 2010):

$$\forall (j,k,l) \in [1;p] \times [1;e] \times [1;m] \beta_{k,j}^l = \frac{\partial h^l / h^l}{\partial b_{k,j} / b_{k,j}} \tag{6}$$

Eqs. (2) to (6) bring about the following relation:

$$\beta_{k,j}^l = -Q^l \times \frac{\partial B}{b_{k,j}} \times s \times \frac{b_{k,j}}{h^l} \tag{7}$$

This environmental flow perturbation factor $\beta_{k,j}^l$ also corresponds to the contribution to the total impact score of the couple {emission k | process j} to the impact l. Consequently, $\beta_{k,j}^l$ can also be calculated as follows:

$$\beta_{k,j}^l = \frac{Q^l \times s_j \times b_{k,j}}{h^l} \tag{8}$$

The sum of all the environmental perturbation factors is always equal to one.

To illustrate these relations, a simple system is presented in Fig. 1. In this system, Q is a vector, which means that only one impact is assessed. Notice that the characterisation factor values given in Fig. 1 have been chosen arbitrarily and do

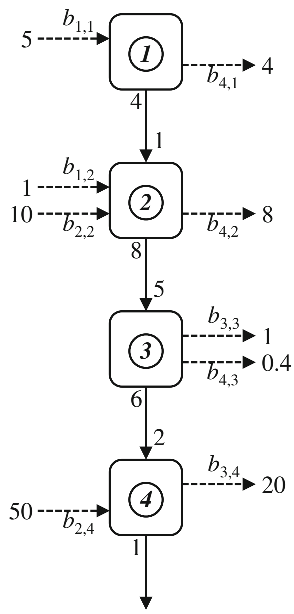

Fig. 1 Example of a simple process tree

not correspond to real characterization factor values. The mathematical description of this system is given by the following elements in Eq. (9).

$$A = \begin{bmatrix} 4 & -1 & 0 & 0 \\ 0 & 8 & -5 & 0 \\ 0 & 0 & 6 & -2 \\ 0 & 0 & 0 & 1 \end{bmatrix} B = \begin{bmatrix} 5 & 1 & 0 & 0 \\ 0 & 10 & 0 & 50 \\ 0 & 0 & 1 & 20 \\ 4 & 8 & 0.4 & 0 \end{bmatrix} \tag{9}$$

$$Q = [\,1 \quad 5 \quad 25 \quad 100\,]\, f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

For this system, the impact score (h) equals 970.05 and

$$\alpha = \begin{bmatrix} -0.0217 & 0.0217 & 0 & 0 \\ 0 & -0.2045 & 0.2045 & 0 \\ 0 & 0 & -0.2268 & 0.2268 \\ 0 & 0 & 0 & -1 \end{bmatrix} \tag{10}$$

$$\beta = \begin{bmatrix} 0.0003 & 0.0002 & 0 & 0 \\ 0 & 0.0107 & 0 & 0.2577 \\ 0 & 0 & 0.0088 & 0.5154 \\ 0.0215 & 0.1718 & 0.0137 & 0 \end{bmatrix}$$

These perturbation factors allow a direct calculation of a new impact score according to a change in a given flow. For example, with a change from −5 to −7.5 for the economic flow $a_{2,3}$ (an increase of 50 %), the new impact score is equal to 1,069.2 according to

$$h_{a(2,3)50\%} = h \times \left(1 + \left(\alpha_{2,3} \times 0.5\right)\right) \tag{11}$$

Perturbation factors are dimensionless because relative variations are used (percentage of variation). The same reasoning can be applied to the environmental perturbation factors.

The structure of α, the perturbation factor matrix of the economic flows, presents some particularities:

– The terms of the diagonal correspond to the perturbation factor of a process output and are strictly negative. All the other terms correspond to process inputs and are positive (except in case of economic flow substitution). The sum of perturbation factors of process inputs increases with the number of processes and loops in the system.
– Except for the reference flow (i.e. non-null value of the final demand f), the sum of a line is equal to zero: this means that the perturbation factor of a process output flow is equal to the sum of the perturbation factors of each corresponding input flows. For example, in Fig. 1, a change of 50 % of the output of process 1 (from 4 to 6) is equal to a decrease of 50 % of the input of process 2 (from 1 to 0.5).

Consequently, to avoid redundant information, the diagonal terms of α are not used in the present approach because sensitivity according to an output is already represented by the sum of the input sensitivities.

For a linear system, the perturbation factor of an economic flow is the sum of all the perturbation factors of the downstream environmental flows (e.g. for the given simple system $\alpha_{2,3} = \sum_{k=1}^{4}\sum_{j=1}^{2}\beta_{k,j}$, the sum of the first two columns of β is equal to 0.2045). In a more realistic situation (a large-size system including parallel pathways and loops), the relations are more complex, but the perturbation factors of economic and environmental flows are always comparable. For example, the consequence on the impact score of a variation of $b_{2,\,2}$ is roughly two times less important than a variation of $a_{1,\,2}$. From $\alpha_{i,j}{}^{l}$ and $\beta_{k,j}{}^{l}$ values, a unique set of ordered flows is defined according to their sensitivity ($\{i, j, l\}$ or $\{k, j, l\}$, both economic and environmental for each process, for all impacts).

2.2 Selection of the relevant sets

From this set of ordered flows, a subset of significant flows has to be defined in order to check whether dynamic flow values are relevant. The size of this subset depends on the approach of the selection criterion. It has to be a balance between a small, easy to describe but unrepresentative subset and one that is large, very representative but difficult to describe. It was decided that if the addition of an extra set

({economic flow | process | impact} or {environmental flow | process | impact}) should induce a variation of more than 1 % of the cumulative sensitivity of the system, then the set is to be selected. In the opposite case, the selection is to be stopped. This selection criterion has been based on an evaluation using different impacts expressed in the same unit rather than one aggregated impact (like the single score). Hence, this methodology is able to determine on which impact category the selected set has an influence and allows a comparison between the timescale of the impact and the timescale of the couple {economic flow | process} (respectively {environmental flow | process}) (see next section). All the impacts with the ReCiPe endpoint method (Goedkoop et al. 2009) are represented: the impacts are normalized (by an average word citizen) and weighted (hierarchical perspective; see ReCiPe documentation), and results are expressed in points, which are defined in the Ecoindicator99 method (Goedkoop and Spriensma 2000) as one thousandth of the impacts generated by an average word citizen.

2.3 Dynamics for the selected flows

2.3.1 Timescale definitions

The relevance of the introduction of a temporal dynamic for a given flow has to be estimated in regard with the timescale of the impact. To be consistent, the timescale of the environmental flows (θ_{ENV}) or the economic flows (θ_{ECO}) and the timescale of the impacts (θ_{IMP}) should be considered.

An emission to the environment from a process is characterized by its own timescale θ_{ENV}. This timescale corresponds to the period during which a significant variation occurs for the considered environmental flow, for a specific process. A typical example is the emission of ammonia from an agricultural crop production linked to the use of fertilisers. This flow is the result of the combination of technical decisions (spreading techniques) and weather conditions (temperature, rain, wind). On one hand, θ_{ENV} is daily based. Nevertheless, for ammonia losses occurring at a fertiliser plant level, the emission dynamic is mainly determined by the evolution of technologies. On the other hand, θ_{ENV} is yearly based. θ_{ENV} allows to take into account the intrinsic dynamic of the process.

As LCA is a function-oriented tool, the system modelling is done in order to fulfil a function, described by the functional unit. Consequently, if θ_{ENV} values depend on the process, in the present work, θ_{ECO} values are established according to the dynamics of the demands. For example, the fertiliser production associated to 1 kg of cereals occurs during a short period of time, and the associated impacts (e.g. acidification) take place within a short timescale. This aspect is taken into account with the dynamic of the economical flow.

All the impacts have inherent characteristics, such as their spatial and temporal scales. The timescale θ_{IMP} defines the time step during which the emissions and resource consumptions are classically aggregated and where the impacts are assessed according to the model that has been used. The dynamic of the impacts from the ReCiPe method is discussed in the following section.

2.3.2 Timescales of the impacts

Table 1 presents the inherent timescales of the impacts considered in this study. A yearly, monthly or daily basis can be determined for an impact according to its features.

Impact timescales equivalent to 1 year concern resource consumptions (except for water depletion), global impacts (climate change, ozone depletion), and impacts related to land (land occupation and land transformation):

– Fossil and mineral consumption generally corresponds to a time constant of 1 year. As these resources are part of a global market with important stocks, depletion is not linked to a local dynamic of consumption (Goedkoop et al. 2009).
– Concerning climate change, global warming potentials (IPCC 2007) are used as characterisation factors with chosen time horizons expressed in years (20, 100 or 500). Some authors have recently developed dynamic characterization functions (Levasseur et al. 2010; Schwietzke et al. 2011), in which the temporal scale used to aggregate the greenhouse gas emissions spans over a year. A specific

Table 1 Timescales associated with the impacts

Impact categories	Timescales θ_{IMP}		
	Day	Month	Year
Climate change (CC)			X
Ozone depletion (OD)			X
Agricultural land occupation (ALO)			X
Urban land occupation (ULO)			X
Natural land transformation (NLT)			X
Mineral resource depletion (MRD)			X
Fossil resource depletion (FD)			X
Terrestrial acidification (TA)		X	
Freshwater eutrophication (FE)		X	
Marine eutrophication (ME)		X	
Water depletion (WD)		X	
Photochemical oxidant formation (POF)	X		
Human toxicity (HT)	X		
Particulate matter formation (PMF)	X		
Terrestrial ecotoxicity (TET)	X		
Freshwater ecotoxicity (FET)	X		
Marine ecotoxicity (MET)	X		
Ionising radiation (IR)	X		

methodology based on yearly differentiation has also been developed by Cherubini et al. (2011) to take into account the CO_2 from biomass combustion.

- Ozone depletion potential is defined as a relative measure of the ozone depletion capacity of an ozone-depleting substance (ODS), using CFC-11 (trichlorofluoromethane) as a reference. It is calculated as a change in the equilibrium state due to annual emissions of an ODS and CFC-11 (Wuebbles 1983).
- Land transformation and land occupation can have various damaging effects on the environment such as degradation of the soil, emissions of CO_2, CH_4 and N_2O and deterioration of species composition. The dynamics of land transformation and occupation generally occur over a year, and changes in the carbon content of the soil are recommended to be measured at intervals of 5-year periods (IPCC 2000).

Timescales equivalent to a month correspond to regional impacts (terrestrial acidification, freshwater eutrophication, marine eutrophication) and water depletion:

- Extracting water from dry areas can cause very significant damage to ecosystems and human health at short- and mid-term horizons. The impact is consequently directly correlated to local exploitation of the resources (Goedkoop et al. 2009), and the appropriate timescale should therefore correspond to a month. Indeed, seasonal variations are capable of strongly affecting water resources.
- The acidification impact is commonly addressed at midpoint level, based on the critical load concept (Seppälä et al. 2006). This impact is either correlated with rainfall (lixiviation of base cation from the soil) or acid rain. Rainfall and acid rains are phenomena related to atmospheric conditions and thus mainly depend on seasonal variations.
- Aquatic eutrophication can be defined as nutrient enrichment of the aquatic environment. Characterization of aquatic eutrophication in LCIA only takes into account nutrients limiting aquatic biomass growth (phosphorus for freshwater and nitrogen for seawater in European regions) (Crouzet et al. 1999). High concentrations of nitrogen or phosphorus in freshwater or in the sea have environmental consequences depending on essentially seasonal variables like temperature and sunlight.

Finally, timescales equivalent to a day correspond to human health (human toxicity, radiation, particulate matter and photo-oxidant formation) and ecotoxicity (terrestrial, freshwater and marine):

- The characterization factors for human toxicity and ecotoxicity account for the environmental persistence (fate), exposure and toxicity (effect) of a chemical substance. The toxicity and the ecotoxicity can be either acute (massive exposure in a short duration) or chronic (prolonged exposure to a more or less important concentration). The evaluation of acute effects implies the selection of a relatively short timescale, over 1 day.
- The framework for human toxicity and ecotoxicity is also applied to ionising radiation: the modelling starts with releases at the point of emission, expressed in becquerel, and calculates the radiative fate and exposure, based on detailed nuclear physics information.
- Particulate matter represents a complex mixture of organic and inorganic substances. It is the cause of various health issues depending on the size of the particles. Exposition to particulate matter can either have an acute or chronic effect, similarly to toxicity.
- Finally photo-oxidant formation is the formation of reactive chemicals like ozone by the action of sunlight on certain primary pollutants (Guinée et al. 2002), according to weather conditions. The potential impact should be lower if the same quantity of a pollutant is emitted only during night-time rather than over a 24-h period. A diurnal timescale would therefore be required in this case.

2.3.3 Introduction of a temporal dynamic

To be consistent, the introduction of a temporal framework should take into account both the timescale of the flow (θ_{ENV} or θ_{ECO}) and the inherent timescale of the impact θ_{IMP}:

- If θ_{ENV} (or θ_{ECO}) and the impact's timescale θ_{IMP} of the selected couple have the same order of magnitude, the introduction of a dynamic model is relevant.
- If θ_{ENV} (or θ_{ECO}) is larger than θ_{IMP}, the introduction of a dynamic should also be considered. Indeed, in this case, the dynamic of the impacts is driven by the slow but existing dynamic of the emissions (respectively the economic flow). The dynamic of the impacts is therefore the same as the dynamic of the emissions shifted by the timescale θ_{IMP}.
- If θ_{ENV} (or θ_{ECO}) is shorter than the impact's timescale θ_{IMP}, the dynamic of the emissions (respectively the economic flow) does not significantly affect its impact. In this case, the emission (respectively the economic flow) is aggregated on the timescale θ_{IMP} and thus could be approximated by their average static value. For example, if the timescale of the emission is a day and the timescale of the impact is a year, there is no need to introduce a model of the environmental flows with a daily timescale. In this case, an average value of the emissions integrated over 1 year is sufficient.

This methodology leads to the selection of a given number of sets {economic or environmental flow | process | impact} based on their perturbation factors and on the relation between their timescale and that of the involved impact. Perturbation

factor values of environmental or economic flows are firstly calculated and ranked in a merged set. Then, a selection is done based on a chosen cut-off decision. Once a limited number of sets is obtained, their environmental or economic timescales (θ_{ENV} or θ_{ECO}) are compared with the inherent timescale of the impact. If these timescales are shorter than the one of the involved impact, the set is not selected. In the other case, the set is selected, and a temporal dynamic can be introduced.

3 Results

To illustrate this approach, we consider two practical case studies based on Ecoinvent Unit processes: "Palm methyl ester, at esterification plant/MY" and "Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR". In both cases, the functional unit is equal to 1 kg.

3.1 Case study from the Ecoinvent database: "Palm methyl ester, at esterification plant/MY"

3.1.1 Overview of the system

The considered system is made up of 1,962 unit processes, and 659 emissions or resource consumptions are listed. There are 39,086 sets, with 21,195 sets {process | environmental flow | impact} and 17,891 sets {process | economic flow | impact}.

3.1.2 Results

Figure 2 represents the values of perturbation factors for the economic (grey) and environmental (black) flows of the ordered sets and their cumulative sum (solid black curve). Using

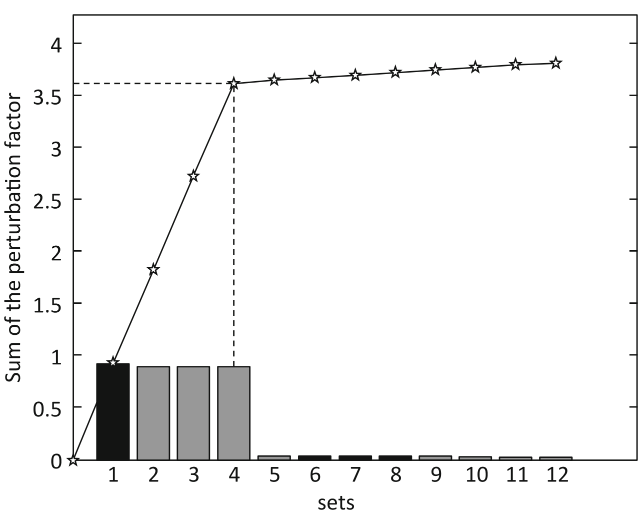

Fig. 2 Selection of relevant sets where a temporal dynamic could be introduced (Ecoinvent case study: "Palm methyl ester, at esterification plant/MY")

the procedure described above, 93.5 % of the sum of all the perturbation factors can be obtained. The number of needed sets to satisfy the criterion selection previously defined is 4, which represents 0.010 % of the total number of sets. There is 1 out of 21,195 (0.004 %) sets {process | environmental flow | impact} selected which represent 83.14 % of the sum of all the environmental perturbation factors and 3 out of 17,891 (0.017 %) sets {process | economic flow | impact} which represent 85.04 % of the sum of all the perturbation economic factors.

Table 2 presents the main information for the selected sets. The impact is in the four selected sets "Natural Land Transformation". Consequently, in accordance with the suggested timescale for the impacts, the timescale is a year. The timescale of all the assessed flows is also a year:

- Transformation, from tropical rain forest: it is supposed that the period during which the transformation takes place is a year.
- Provision, stubbed land/MY: This flow is an input of the process "Palm fruit bunches, at farm/MY". The palm bunches can be harvested throughout the year, so the timescale is a year. The same reasoning is made to determine the timescales of the economic flows "Palm fruit bunches, at farm/MY" and "Palm oil, at oil mill/MY".

Consequently, the introduction of time in all the selected sets by the sensitivity analysis is relevant.

3.2 Case study from the Ecoinvent database: "Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR"

3.2.1 Overview of the system

The considered system is made up of 1,959 unit processes, and 659 emissions or resources consumptions are listed. There are 39,113 sets, with 21,221 sets {process | environmental flow | impact} and 17,892 sets {process | economic flow | impact}.

3.2.2 Results

The chart legend of Fig. 3 is the same as that of Fig. 2. In this unit process, 57.8 % of the sum of all the perturbation factors is obtained. The number of needed sets to satisfy the criterion selection previously defined is 41, which represents 0.1 % of the total number of sets. There are 14 out of 21,221 (0.07 %) sets {process | environmental flow | impact} selected which represent 67.3 % of the sum of all the environmental perturbation factors and 27 out of 17,892 (0.15 %) sets {process | economic flow | impact} which represent 39.2 % of the sum of all the perturbation economic factors.

Table 3 presents the main information for the first ten sets. The timescales of the involved environmental and economic flows are different:

Table 2 Characteristics of the selected couples for the process "Palm methyl ester, at esterification plant/MY"

Perturbation factor value	Type of the flow	Name of the flow	Name of the process	Impacts	θ_{IMP}	θ_{ENV} or θ_{ECO}	Selection
0.921	Environmental	Transformation, from tropical rain forest	Provision, stubbed land/MY	Natural land transformation	Year	Year	Yes
0.893	Economic	Palm fruit bunches, at farm/MY	Palm oil, at oil mill/MY	Natural land transformation	Year	Year	Yes
0.893	Economic	Palm oil, at oil mill/MY	Palm methyl ester, at esterification plant/MY	Natural land transformation	Year	Year	Yes
0.893	Economic	Provision, stubbed land/MY	Palm fruit bunches, at farm/MY	Natural land transformation	Year	Year	Yes

– Occupation, arable, non-irrigated: the occupation of the arable land occurs as long as the farming activity is present (several years).
– Disposal, wood ash mixture, pure, 0 % water, to land farming/CH and phosphorus: waste management and the corresponding emissions are generally assessed over a yearly based timescale.
– Natural gas, at long-distance pipeline/RER: natural gas can be stored, so the relevant timescale of this economic flow is a year.
– Sugarcane, at farm/BR: The sugarcane is harvested once a year, just before the flowering, so the timescale is equivalent to a month.
– Nitrogen oxides and particulates, <2.5 μm: these compounds are continuously emitted by the factory of ethanol production. The emissions can vary, depending on how the plant functions. It is assumed that the plant is operational on a month-based timescale (after the harvest of the sugarcane), so the timescale of the emissions is a month.

The comparison of the environmental and economic timescales with the timescales of the different impacts leads to the exclusion of eight sets, so the final number of selected sets is 33.

This analysis highlights the fact that in the two examples from the Ecoinvent database, a limited number of sets is enough to correctly assess where it would be relevant to introduce time in the LCI.

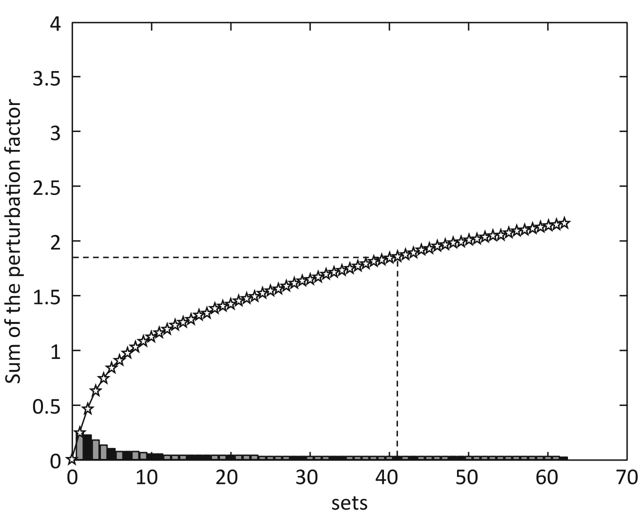

Fig. 3 Selection of relevant sets where a temporal dynamic could be introduced (Ecoinvent case study: "Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR")

4 Discussion

The proposed methodology is a first step towards the introduction of a relevant temporal dimension in the LCI. It is based on sensitivity analyses and on the definition of inherent timescales for the impacts and specific timescales for the different flows. The cut-off decision has been chosen in order to represent the maximum of relevant information with the selection of a limited number of sets. Depending on the available time to conduct the study, an iterative approach could also be undertaken. The evaluation of the relevance of the introduction of time is done on the first set and then on the second one, etc. The number of selected and analysed sets could depend on the expendable time of the LCA practitioner and of the nature of the studied system.

The comparison between the different sets is done as a result of the expression of all the perturbation factors in the same unit (in Point). The results are consequently only expressed in one dimension. The calculation of the perturbation factors may also have been done for each impact, and so the obtained results would have been in *n* dimensions (with *n* the number of considered impacts). This approach overcomes the subjectivity introduced by choice for an endpoint approach (as individualist, egalitarian and hierarchical perspectives) but implies a multi-criteria decision problem. Consequently, a multiple-criteria decision-making approach should be used in order to rank the perturbation factors depending on the assessed impacts. The developed methodology in this study could then be applied to select the relevant sets. Furthermore, at the LCIA level, time introduction is assumed to be consistent for all the impacts in this approach. Indeed, it is implicitly suggested that the calculation of impact scores with dynamic

Table 3 Characteristics of the selected couples for the process "Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR"

Perturbation factor value	Type of the flow	Name of the flow	Name of the process	Impacts	θ_{IMP}	θ_{ENV} or θ_{ECO}	Selection
0.223	Economic	Sugar cane, at farm/BR	Ethanol, 95 % in H2O, from sugar cane, at fermentation plant/BR	Agricultural land occupation	Year	Month	No
0.223	Environmental	Occupation, arable, non-irrigated	Sugar cane, at farm/BR	Agricultural land occupation	Year	Year	Yes
0.167	Economic	Sugar cane, at farm/BR	Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR	Fossil depletion	Year	Month	No
0120	Economic	Sugar cane, at farm/BR	Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR	Climate change human health	Year	Month	No
0.091	Environmental	Particulates, <2.5 μm	Ethanol, 95 % in H_2O, from sugarcane, at fermentation plant/BR	Particulate matter formation	Day	Month	Yes
0.068	Economic	Disposal, wood ash mixture, pure, 0 % water, to land farming/CH	Ethanol, 95 % in H_2O, from sugarcane, at fermentation plant/BR	Human toxicity	Day	Year	Yes
0.067	Environmental	Phosphorus	Disposal, wood ash mixture, pure, 0 % water, to landfarming/CH	Human toxicity	Day	Year	Yes
0.062	Economic	Sugar cane, at farm/BR	Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR	Particulate matter formation	Day	Month	Yes
0.050	Economic	Natural gas, at long-distance pipeline/RER	Natural gas, high pressure, at consumer/RER	Fossil depletion	Year	Year	Yes
0.039	Environmental	Nitrogen oxides	Ethanol, 95 % in H_2O, from sugar cane, at fermentation plant/BR	Particulate matter formation	Day	Month	Yes

LCI would lead to different results. However, just a few impacts are based on dynamic functions of characterization instead of static characterization factors: human toxicity (Manneh et al. 2012), climate change (Brandão et al. 2013; Cherubini et al. 2011; Levasseur et al. 2010, 2012; Schwietzke et al. 2011), photochemical oxidation (Shah and Ries 2009) and noise (Cucurachi et al. 2012). Further research is therefore needed to identify impacts where the dynamic has to be taken into account and to develop specific functions of characterization.

As stated by Heijungs and Suh (2002), delays are an important component in constructing a dynamic model. In our approach, we principally focus on the identification of the most sensitive flows. A change in an economic flow is supposed to induce instantaneous changes in the downstream environmental flows. However, a physical "storage" of economic flows at the LCI level can occur, which engenders a period of time between the production of the economic flow and its use. It is suggested that depending on the nature of the trade linked with this economic flow, the delay could be different. Two main characteristics are of interest: is the economic flow storable, and could it be provided by several suppliers (atomistic market)? A typology for economic flows could then be done to integrate this additional information. It should be noticed that taking into account the waiting times in economic flows only changes their relative timescale θ_{ECO} without changing the general methodology for selection of sets. These delays underline the importance of timing of emission, which can be essential especially for end-of-life processes where emissions occur after a long time. Storage and delays have to be considered for a propagation of the time relation into the process tree of the inventory. Another kind of storage can also occur at the LCIA level, between the instant the pollutant is emitted into the environment and its translation into impact. These delays can be important, especially when the receiving compartment of the emissions is not the one where the impact occurs.

These two aspects of storage (at the LCI level for economic flows and at the LCIA level for emissions/resource consumptions) should be integrated in the selection of flows where time integration would be relevant. This would be particularly necessary for impacts with a finite integration time horizon (like climate change Levasseur et al. 2010 or metal ecotoxicity Lebailly et al. 2013), in order to avoid overestimation of impact intensity. Such delays should also be taken into account in prospective LCA to know whether or not delays are longer than the time horizon chosen for the study.

Dynamic LCI allows for a dynamic LCIA, and both have to be related. A relevant way to integrate dynamic processes is to introduce distributed emissions, as proposed by Levasseur et al. (2010). In a practical point of view, as only a few flows are selected, the integration of a temporal dimension can be done. Computation of the assessed impacts is firstly carried out with the static approach. Then the impacts corresponding to the selected flows are removed; afterwards, a dynamic LCI (i.e. distributed emissions and/or resource consumptions) is generated for the selected flows, and new impacts are calculated for these flows using dynamic LCIA (i.e. characterization functions instead of characterization factors).

5 Conclusions

This work proposes a methodology for specifying where the introduction of temporal dynamics is the most relevant in a whole process tree. It is based on sensitivity analyses on environmental and economic flows. The introduction of a dynamic depends on the relation between the timescales of the flows and the timescale of the involved impact. While θ_{ECO} and θ_{ENV} are directly linked to the process where they occur, θ_{IMP} can be defined more generally.

The definition of θ_{IMP} may change according to the selected impact assessment or to the chosen cultural perspective. For instance, in an individualist perspective (Thompson et al. 1990) based on short-term interest, the timescale of the ionising radiation impact would be a day, whereas in an egalitarian one, which takes into account the longest timeframe, it would rather be a year or a century. The description of the respective timescales for each impact could be a subject of future development in LCIA methods.

The time-distributed LCI which could be generated using this approach can be coupled with dynamic LCIA methods in order to have a full dynamic LCA. Finally, the criterion leads to the exclusion of some couples with an important impact score. It should also be useful to develop models for these couples because the generation of a dynamic LCI would lead to a more precise evaluation of emissions that could be integrated over time and hence be used in a classical LCA approach.

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